Investigation of the Seasonal Freeze/Thaw Cycle of Soils in the GAPP Regions

(NOAA GAPP Project: NA06GP0582)

Annual Report (third year)

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Introduction

Understanding cold season atmosphere-hydrosphere interactions and their feedback in Earth's weather and climate system is essential for assessing variations in the regional and global energy and water cycles. This is a critical and integral component of both the Global Water and Energy Experiment (GEWEX) and the NOAA's Climate and Global Change Program. Important components of the terrestrial hydrology are soil water freezing and thawing processes. Freeze/thaw cycles influence the thermal and hydrologic characteristics of the soil, which have a significant impact on the surface energy and water balance, and hence on weather and climate systems, and surface and subsurface hydrologic processes such as river runoff and soil moisture.

On average, about 60% of the contiguous United States experiences soil freezing during winter (Zhang and Armstrong, 2001). However, the timing and duration, thickness, and areal extent of soil freezing may be changing spatially and temporally. In fact, some results indicate that during the past few decades, the extent of seasonally frozen ground in the contiguous United States has decreased substantially (Zhang, 2002). Better knowledge and understanding of the near-surface soil thermal regime and the seasonal freeze/thaw cycle of soils are prerequisite for evaluating the potential impact of cold season/region processes on hydrology, climate, carbon exchange, and the ecosystem as a whole.

Overall Objective of the Project

The objective of this project is to understand the current and future impacts and feedbacks of seasonally frozen ground on the regional and global climate system and the ecosystem as a whole. More specifically, we proposed to:

- Investigate the dynamics of the seasonally freezing and thawing processes and their relations to current climatic conditions through in situ data analysis and numerical modeling;
- Develop a comprehensive algorithm to detect surface soil freeze/thaw status for snow-free land surface using passive microwave remote sensing data and for snow-covered land surface using numerical modeling, and validate the algorithm and numerical model using available ground-based measurements;
- Investigate seasonal and inter-annual variations of frozen soils in the GAPP regions using data generated from the new validated algorithm and their relations to the environmental factors such as air temperature, snow cover, surface morphology, soil type and soil moisture;
- Generate a frozen soil data set which describes the timing, duration, thickness, and area extent of seasonally frozen ground for the period from 1978 to present.

The proposed research will be accomplished through data analysis, remote sensing, and numerical modeling.

In our original proposal, the tasks for the third year were stated as follows:

"Year 3: complete all runs with SMMR and SSM/I data for the period from 1978 to present. Analyze the data and present new findings to scientific community, prepare and submit journal publications. Finalize data products and submit to the GAPP for archive and distribution." In the following sections, we will describe the major results and accomplishments.

Results

A combined frozen soil algorithm was developed and validated to detect the near-surface soil freeze/thaw cycle over snow-free and snow-covered land areas in the contiguous United States. The combined frozen soil algorithm consists of two parts (Figure 1): (i) over snow-free land areas, a passive microwave remote sensing algorithm was used to detect the near-surface soil freeze/thaw cycle; (ii) over snow-covered land areas, a one-dimensional numerical heat transfer model with phase change was used to detect soil freeze/thaw status under snow cover. Using the Defense Meteorological Satellite Program's Special Sensor Microwave Imager (SSM/I) data, the passive microwave algorithm uses a negative spectral gradient between 19 GHz and 37 GHz, vertically polarized brightness temperatures, and a cut-off brightness temperature at 37 GHz with vertical polarization (T_B(37V)). SSM/I data and Soil temperature data from 26 stations over the contiguous United States from two year period, July 1, 1997, through June 30, 1999, were used to calibrate the algorithm (year 1), to validate the algorithm (year 2), and to demonstrate freeze/thaw classification (both years). A cut-off brightness temperature of 258.2K was obtained based on a linear correlation (r^2=0.84) between the soil temperature at 5 cm depth and the T_B(37V) (Figure 2). The combined frozen soil algorithm provides the accuracy for frozen soil detection of about 76% and the accuracy for the correct classification of both frozen and unfrozen soils of approximately 83% with a percent error of about 17%.

For the first time, the combined frozen soil algorithm was used to investigate the timing, duration and number of days, and daily area extent of near-surface frozen soils over the study area. The primary results indicate that:

i) Near-surface soil freezing started in the northern Great Plains and along the Rocky Mountains in October and November, gradually expanded into northern states as the winter progressed, and finally retreated back in the spring (Figure 4)

ii) The maximum area extent of seasonally frozen ground during the winter of 1997/1998 was about 4.4 x 10^6 km^2 or 63% of the total land area of the contiguous United States, while during the winter of 1998-1999, the maximum area extent was about 5.2 x 10^6 km^2 or 74% of the total study area. The maximum area extent over the two winters occurred in late December and early January.

iii) Area extent of seasonal snow cover was substantially less than that of seasonally frozen ground. The maximum extent of snow cover was about 2.8 x 10^6 km^2 or 40% of the total land area of the contiguous United States during the winter of 1997/98, and 2.5 x 10^6 km^2 or about 35% of the total study area during the winter of 1998/99. The maximum area extent of snow cover occurred in March during these two winters.

iv) During the early winter, the area of frozen soil over snow-free ground dominated the total frozen soil area. As winter progressed and snow cover area expanded, frozen soil under snow cover dominated the total frozen soil area. Due to the insulating effect of snow, frozen soil under snow cover may be thawed by the end of winter. Area extent of unfrozen ground under seasonal snow cover was relatively small, the maximum extent by the end of winter was about 0.34 x 10^6 km^2, accounting for about 7% of the maximum frozen area or less than 5% of the study area.

v) The duration of soil freeze ranged from less than one month in the south to over nine months in the Rocky Mountains. The actual number of days of soil freezing varied from a few weeks to several months (Figure 5).

vi) The number of the near-surface soil freeze/thaw cycles varied from one to more than 11 during the winters of 1997/98 and 1998/99, while the average length of frozen period varied from less than 20 days to more than 220 days (Figure 5).

vii) Frequency of freeze/thaw cycles changes significantly, varying from one to more than 10 per winter season (Fig. 6). The length of the freeze/thaw cycle also varied from less than 20 days to few months (Fig. 6).

viii) Both the maximum and integrated frozen area from 1987 through 2000 changed significantly, with an inter-annual variation by more than 20% (Fig. 8).

One important parameter – daily soil freezing depth of seasonally frozen ground – has not been included in this study. In principle, the combined frozen soil algorithm is capable of predicting daily soil freezing depth. In addition to air temperature and snow cover, there are many other factors that influence soil freezing depth, such as ground surface temperature, soil type, structure, density, soil moisture content, and deep geothermal heat fluxes. To detect soil freezing depth, the combined frozen soil algorithm requires inputs of all of these parameters, especially soil moisture content which changes significantly with time and has a great impact on soil thermal properties. Soil moisture also has a substantial influence on the amount of latent heat of fusion due to phase change when soil water freezes. The lack of these data sets at regional scales limits the capability of the combined frozen soil algorithm to detect soil freezing depth. When these data sets are available in the future, especially soil moisture content within the top meter of soils, soil freezing depth can be detected with confidence. Further validation is needed to improve the accuracy of frozen ground detection and to estimate thickness of the seasonally frozen ground using the combined frozen soil algorithm. Extensive field measurements, especially ground-based radiometer brightness temperature measurements, are needed to further calibrate and validate the combined frozen soil algorithm. These works certainly need more effort and additional funding.

Publications:

We have published five (5) peer reviewed articles, two (2) submitted, two (2) are in preparation, and two (2) published in conference proceedings. Numerous reports, abstracts, oral and postal presentations have been made from this research.

Peer Reviewed Publications

[1]. Ling, F. and **T. Zhang**, 2003. A surface energy balance approach based finite difference model for thermal regime of permafrost containing unfrozen water, Cold Regions Science and Technology, (accepted).

[2]. **Zhang, T**., R. L. Armstrong, and Jeff. Smith, 2003. Monitoring the near-surface soil freeze/thaw cycle in the contiguous United States using a combined frozen soil algorithm, 1: algorithm development and validation, J. Geophys. Res. (accepted).

[3]. **Zhang, T.**, R. G. Barry, and R. L. Armstrong, 2001. Application of remote sensing techniques to frozen ground study, Progress in Physical Geography, (in press).
[4]. **Zhang, T.** and R. L. Armstrong, 2001. Soil freeze/thaw cycles over snow-free land detected by passive microwave remote sensing, Geophysical Research Letters, 28(5), 763-766.
[5]. **Zhang, T**., R.G. Barry, K. Knowles, F. Ling, and R.L. Armstrong, 2003. Distribution of seasonally and perenially frozen ground in the Northern Hemisphere, Proceedings of the 8th International Conference on Permafrost, Zurich, Switzerland, July 2003, (in press).

Submitted Manuscripts:

[1]. **Zhang, T.** and R. Armstrong, 2002. Influence of the seasonal snow cover on the ground thermal regime, Polar Geography.
[2]. **Zhang, T.** and R. G. Barry, 2002. Inter-decadal variations of area extent of seasonally and intermittently frozen ground in the Northern Hemisphere, submitted to Polar Geography.

Manuscript in preparation:

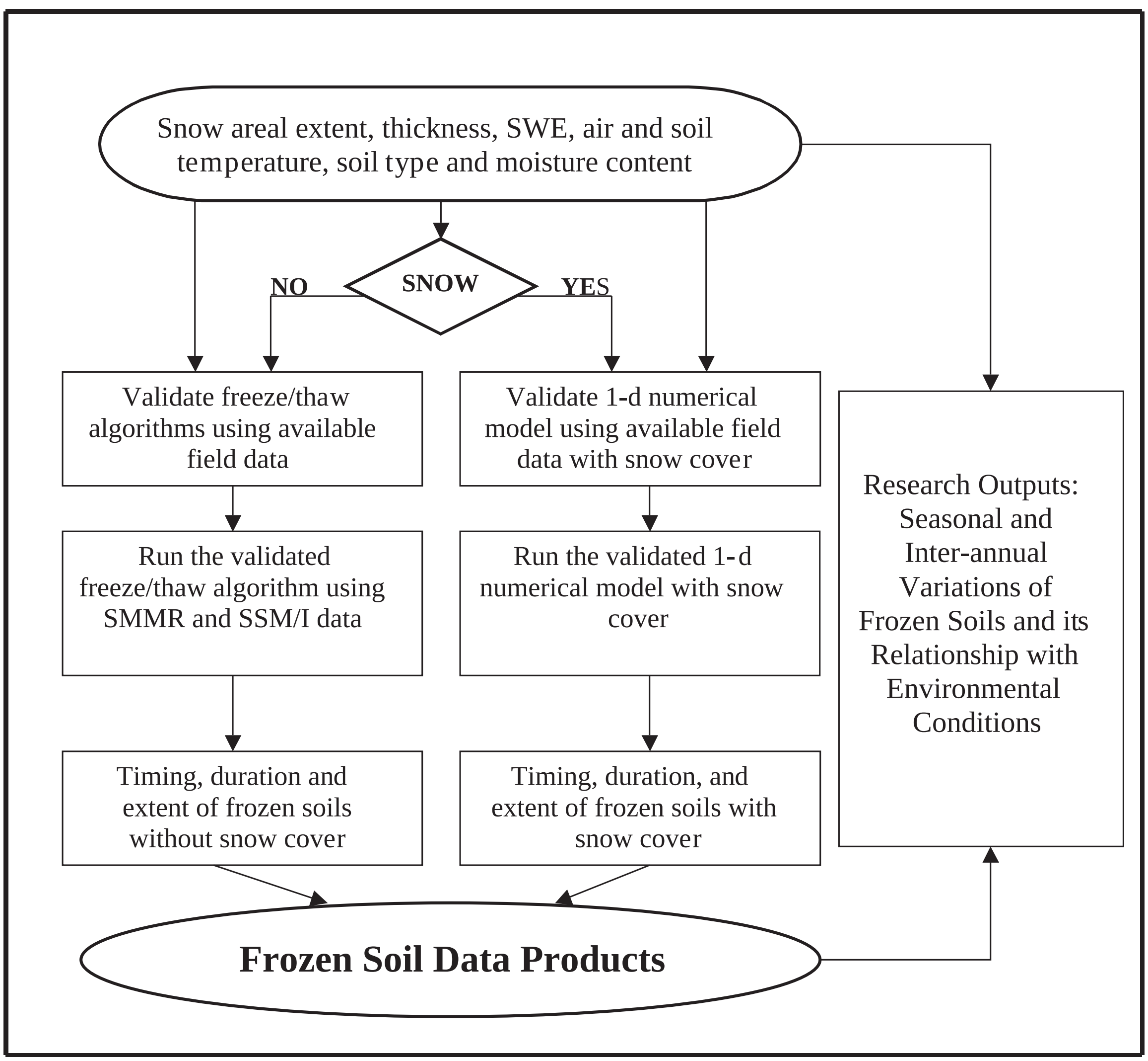
[1]. Zhang, T. and R. L. Armstrong, 2003. Monitoring near-surface soil freeze/thaw cycle in the contiguous United States using a combined frozen soil algorithm, 2: seasonal and inter-annual variations, target to J. Geophys. Res.
[2]. Zhang, T., R. G. Barry, and R. L. Armstrong, 2003. Climatology of the areal extent of the seasonally frozen ground in the contiguous United States, target to J. Hydrometeorology.

Proceedings:

[1]. **Zhang, T.** and R. L. Armstrong, 1999. Passive microwave remote sensing of frozen soils, in Proceedings of the Third International Scientific Conference on the Global Energy and Water Cycle, Jointly with the Fourth Study Conference on GEWEX Asian Monsoon Experiment (GAME), 16-19 June, 1999, Beijing, China, Preprint Volume, Supplementary Collection, pp. 19-21.
[2]. **Zhang, T**., R. Armstrong, and J. Smith, 1999. Detecting seasonally frozen soils over snow-free land surface using satellite passive microwave remote sensing data, Proceedings of the 5th Conf. on Polar Meteorology and Oceanography, 10-15, Jan. 1999, Dallas, Texas.

Presentations: Numerous oral and postal presentations have been made through this research in the past three years.

Figures



Snow areal extent, thickness, SWE, air and soil temperature, soil type and moisture content
NO
SNOW
YES
Validate freeze/thaw algorithms using available field data
Validate 1-d numerical model using available field data with snow cover
Research Outputs: Seasonal and Inter-annual Variations of Frozen Soils and its Relationship with Environmental Conditions
Run the validated freeze/thaw algorithm using SMMR and SSM/I data
Run the validated 1-d numerical model with snow cover
Timing, duration and extent of frozen soils without snow cover
Timing, duration, and extent of frozen soils with snow cover
Frozen Soil Data Products

Figure 1: Flow chart of the Frozen Soil Algorithm.

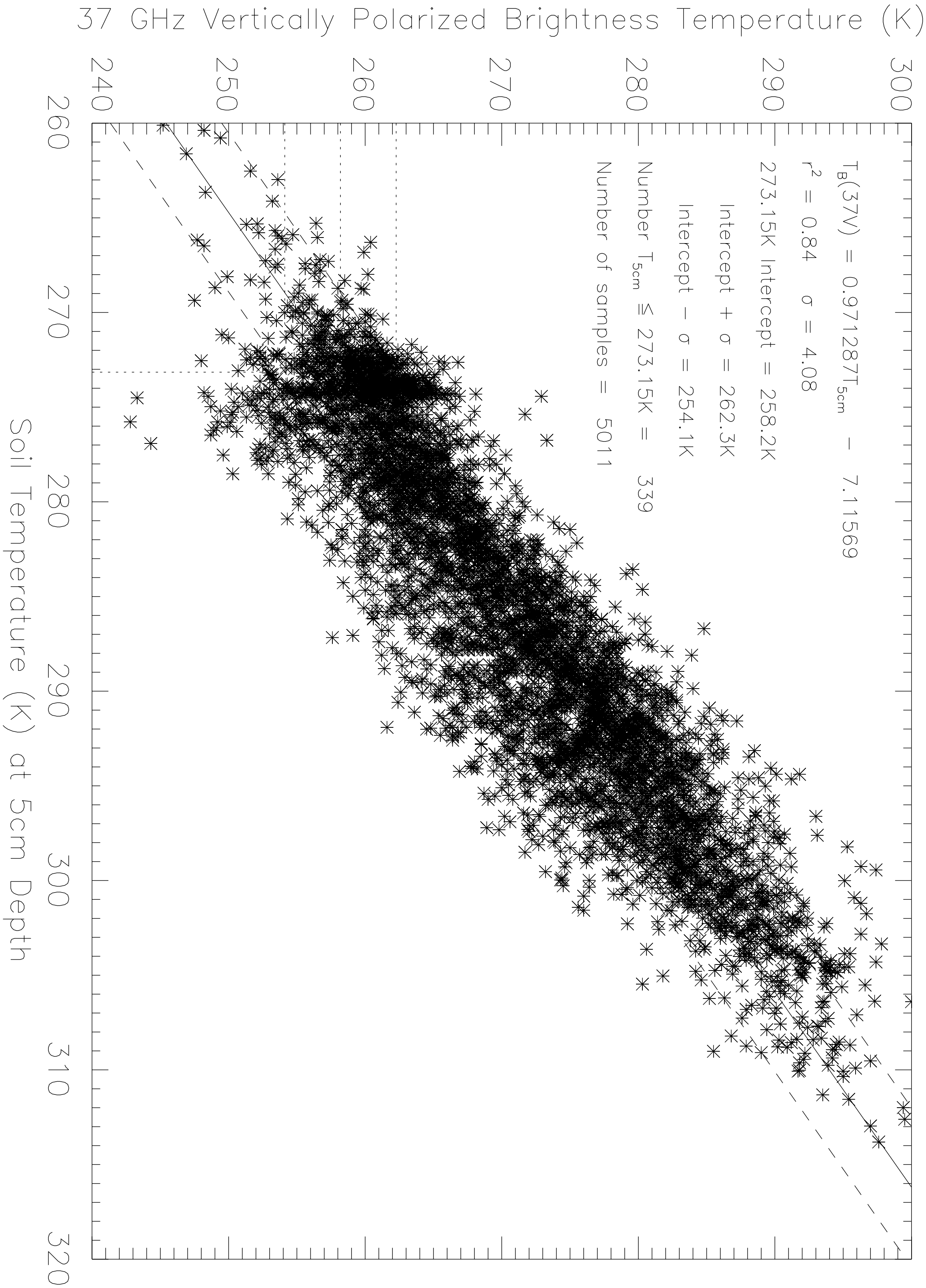


Figure 2: Correlations between the T_B(37V) and soil temperature at 5 cm depth. Soil temperature data were obtained from more than 20 stations over the GAPP areas.

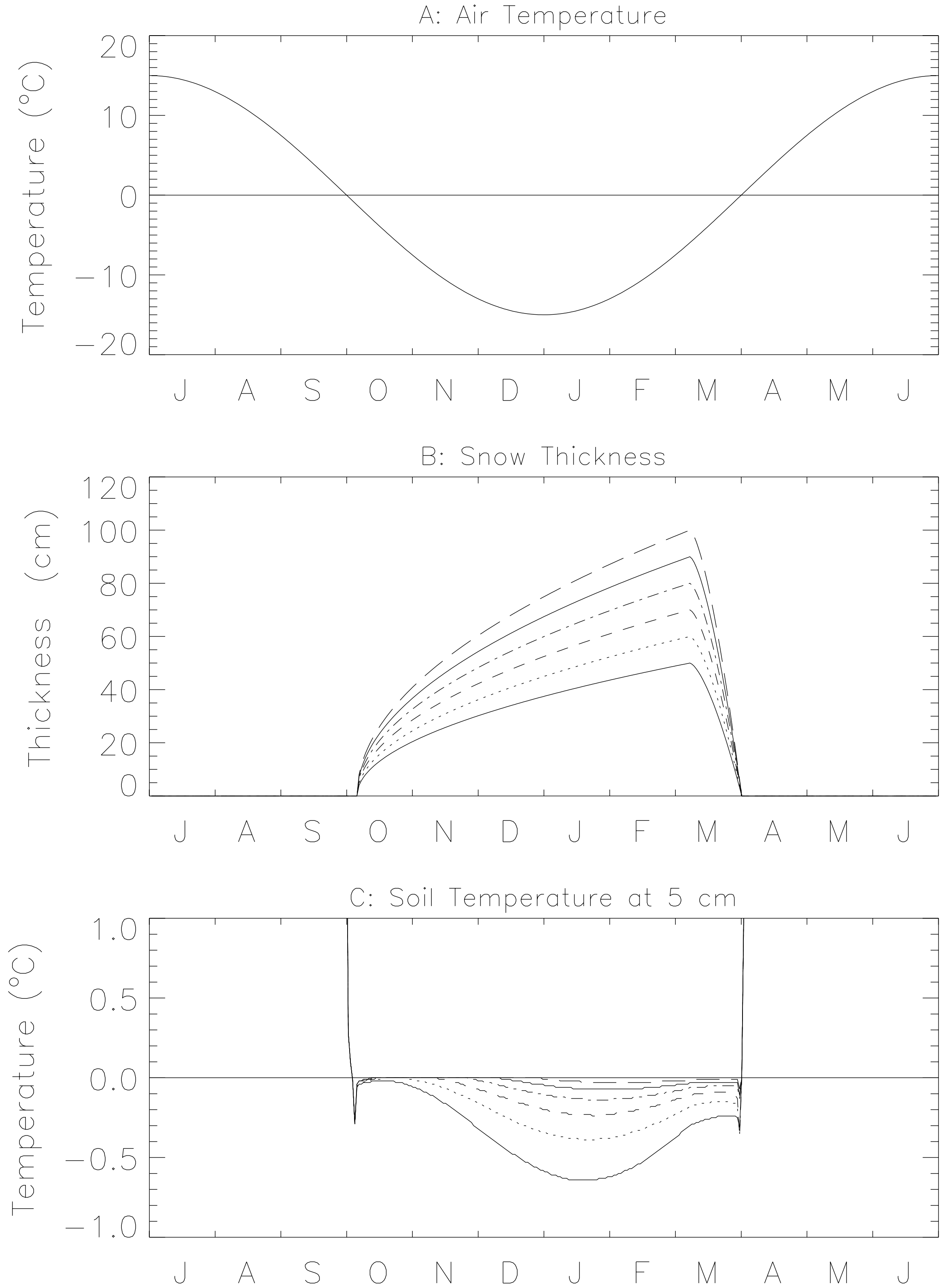


Figure 3: simulation results of a one-dimensional numerical model on determining soil freeze/thaw status under seasonal snow cover.

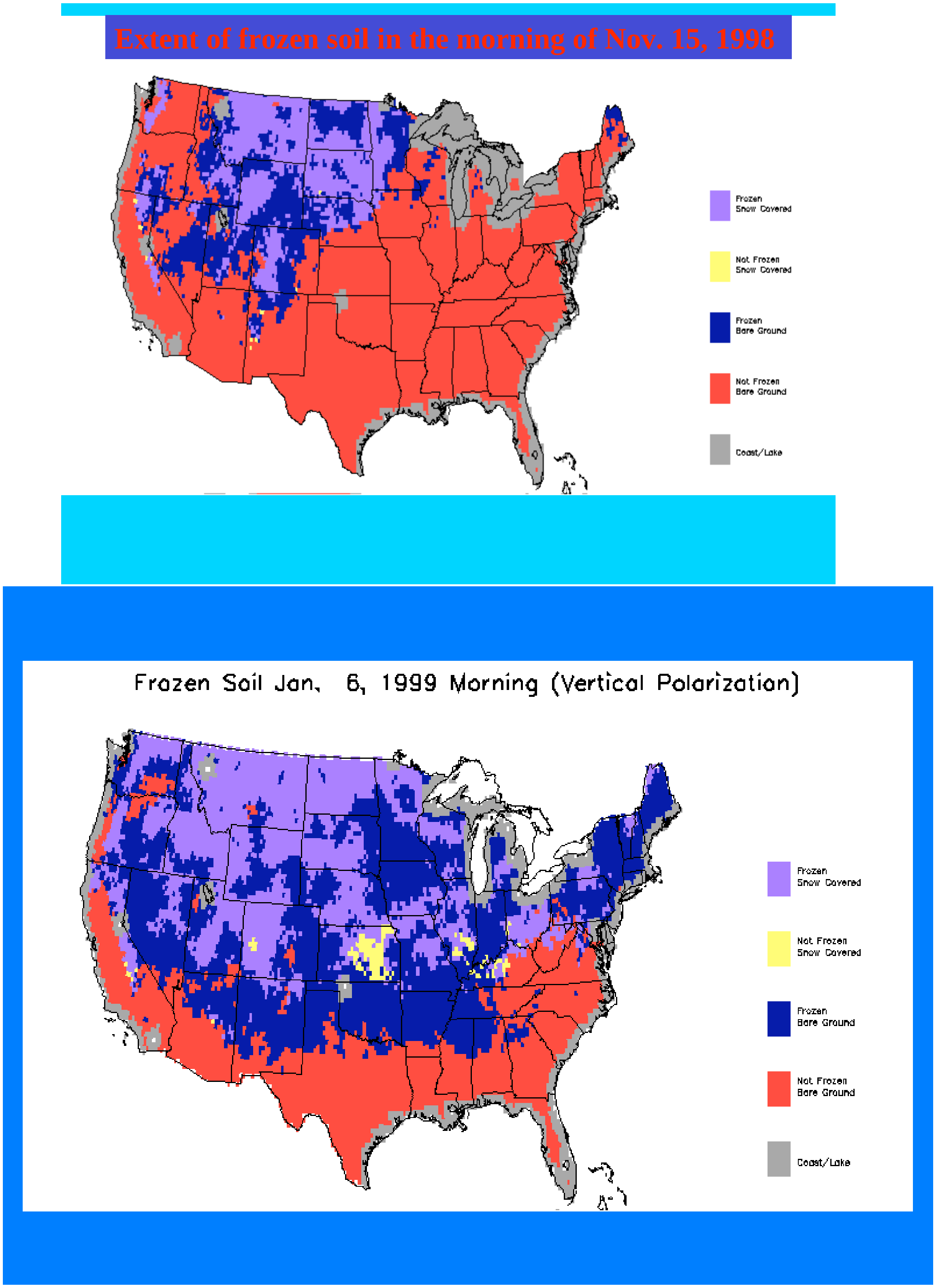


Figure 4. Areal extent of seasonal snow cover and frozen soils in the contiguous United States detected using passive microwave remote sensing data and numerical modeling.

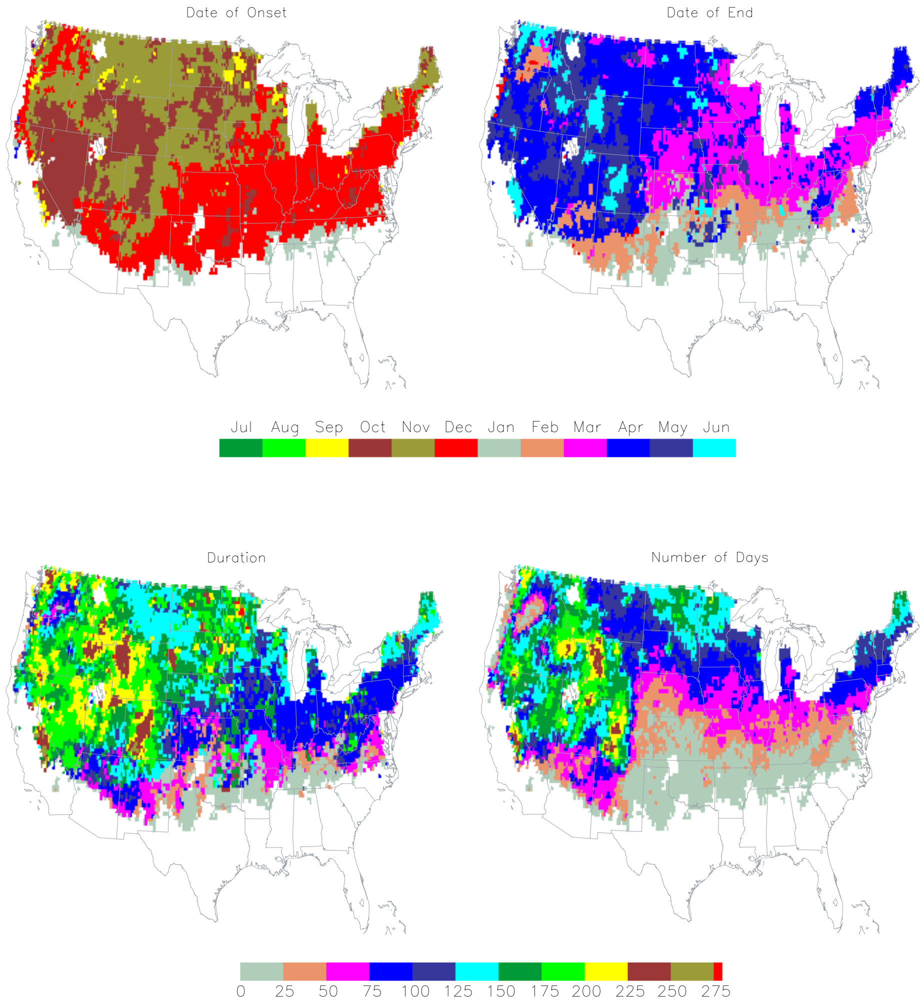


Figure 5. Variations of the timing, duration, and number of days of the near-surface soil freeze/thaw status in the contiguous United States.

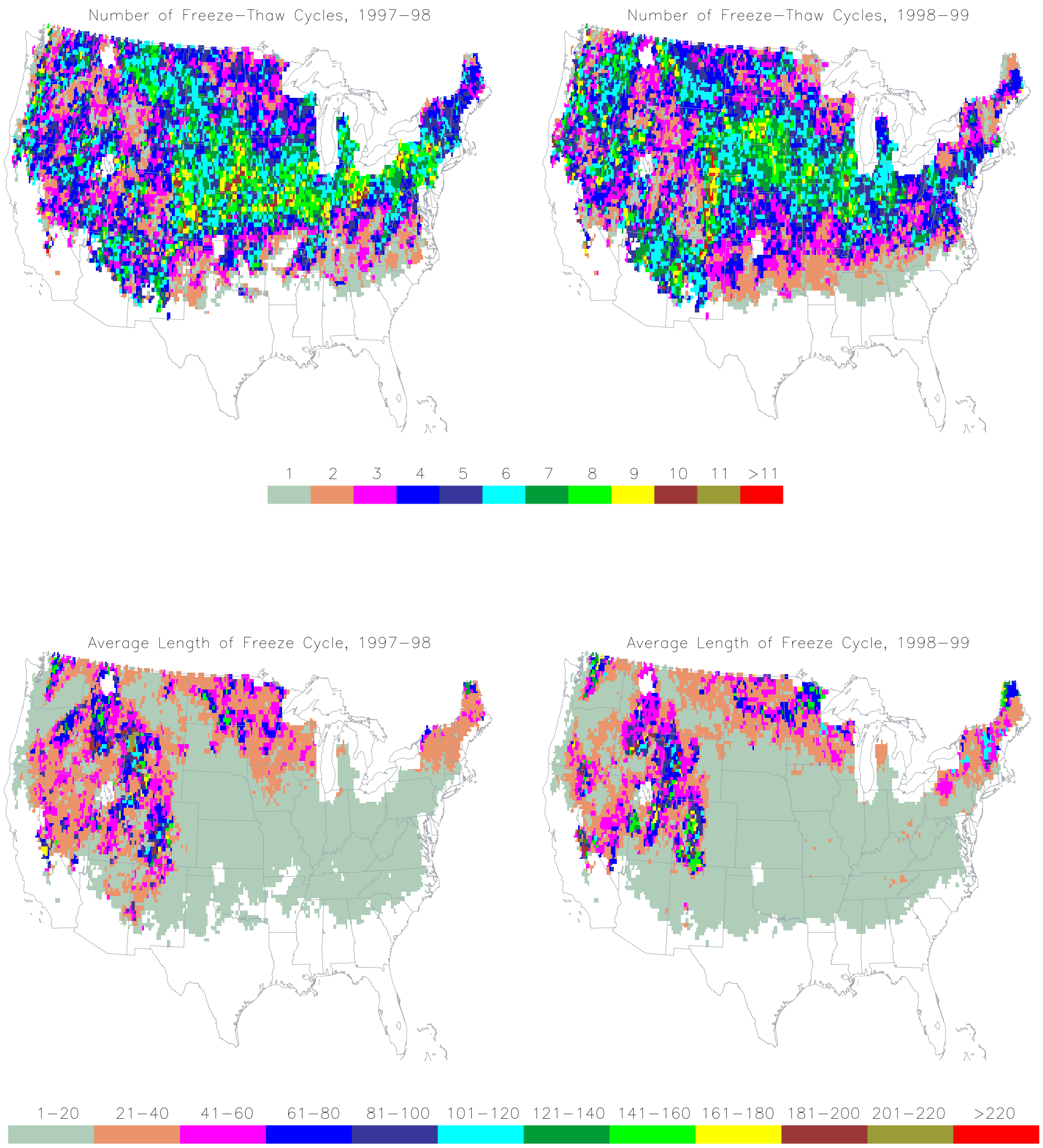


Figure 6. Frequency and length of the near-surface soil freeze/thaw cycle in the contiguous United States in the winters of 1997/98 and 1998/99.

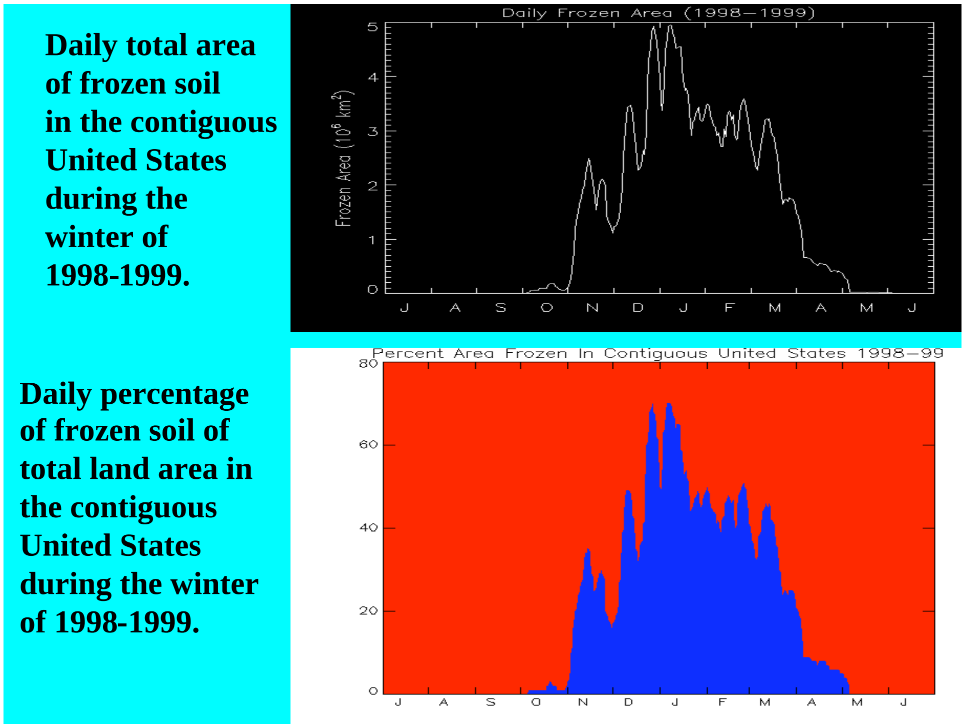


Figure 7. Daily total area (top) and percentage fraction of frozen soil of the total land area in the contiguous United States.

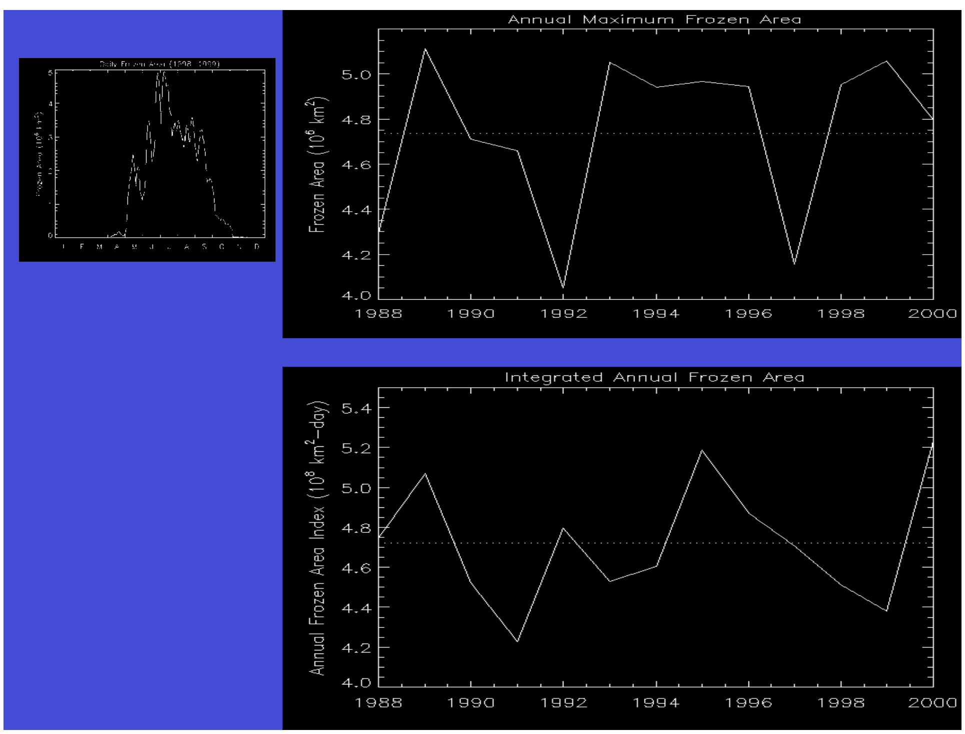


Figure 8. Inter-annual variations of maximum and integrated frozen area in the US from 1987 through 2000.